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DISTRIBUTED ELECTRIC PROPULSION FOR SMALL BUSINESS AIRCRAFT
A CONCEPT-PLANE FOR KEY-TECHNOLOGIES INVESTIGATIONS

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Electrical architecture, handling qualities

Abstract

Electric propulsion for aircraft begins to be effective in the field of leisure aviation mainly for initial training. However, some challenges appear when performance-level needs to be increased to address more demanding application such as business travel even for small passenger capacity. Based on its expertise in all disciplines of aviation design, and in the following of projects dedicated to future Air Transport System, ONERA started exploratory studies, a few years ago, to investigate potential new technologies and concepts that could participate in answering societal need for On-Demand Mobility. The resulting concept-planes illustrate some possible assembly of such key-technologies (KT) which will serve as basis for future research aiming at demonstrating both performance potential and feasibility of the most relevant technologies.

On this basis, ONERA started recently a CARNOT funded project, called AMPERE, dedicated to increase maturity of one of those KT which concerns Distributed Electric Propulsion (DEP), from two main points of view: aero-propulsion and command & control using Electric Ducted Fans (EDF).
This paper intends to describe concept-planes which illustrate the multidisciplinary balance between KTs and then gives some information regarding the DEP dedicated project mentioned above.

1 Introduction

Environmental considerations, in terms of noise as well as pollutant emissions [1][2], in addition to the potential reduction of carbon-based natural resources, lead to investigate the use of electric propulsion for transportation.

Generally based on a pragmatic approach, several manufacturers are investigating the possibility to substitute, on an existing airframe, piston engine(s) for a lithium-polymer or lithium-ion battery powered electric motor with a conventional propeller, connected to an electronic control unit. Performances, such as take-off distance, climb and cruise speed appear to be adequate for very light aircraft having a rather short range and low cruise speed, but a strong challenge appears when trying to extend the range beyond one hour of flight (excluding reserves): due to the energy density of such batteries, their mass increases rapidly leading to redesign the aircraft, larger and heavier, reducing the expected economic viability, for a same payload.

In order to contribute to the growth of this emerging market by investigating some potential solutions coping with the main issues of electric propulsion for aircraft, ONERA decided in 2011 to start an expert-based exploratory study, done in association with CEAtech. This expert-group concluded [3] that there is a potential for all-electric powered airplanes for civil transportation based on the association of several key-technologies integrated in a new airframe configuration using distributed propulsion, in addition to some changes in operational use. Breakthrough technologies concern:

- Distributed propulsion;
- Electric Ducted Fan (EDF);
- Energy supplying, storage and hybrid capabilities;

- Command and control through the association of multi-motors and control surfaces;
- Modular architecture and in-flight reconfiguration capabilities of the overall electric propulsion system;
- Improved multidisciplinary design and optimization capabilities.

Several relevant sets of those key-technologies have been used in order to assess their performances and to show their pros and cons in an overall aircraft design approach. These assessments highlighted trends which led the expert-teams to conclude on the feasibility of electric powered aircraft using distributed propulsion. They also showed that the use of Distributed Electric Propulsion (DEP) adds some new interdisciplinary coupling but also opens new degrees of freedom for the design of airplanes which lead to new compromises.
Assessments were done using a simplified multidisciplinary approach based on a tool able to model several kinds of Propulsion & Power Systems (PPS) and to introduce them into an OAD (Overall Aircraft Design) approach able to size, at a conceptual design level, an aircraft for a given mission, as illustrated in Fig. 1.

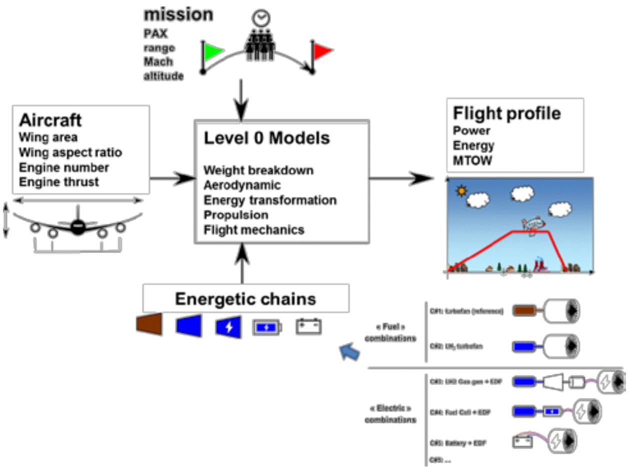

Fig. 1: OAD approach

PPS or Energetic chains modelled use three set of parameters that correspond to three horizons of maturity (state of the art, 2030 and 2050 & beyond) (see Fig. 2 for the list of parameters for key-technologies considered).

Technology	Parameter
Fuel Cells	Efficiency
	Specific power (W/kg)
Battery	Energy density (Wh/kg)
Electric conversion	Efficiency
	Specific power (W/kg)
Electric generation	Efficiency
	Specific power (W/kg)
Gas turbine	Efficiency
	Specific power (W/kg)
Electric Motor	Efficiency
	Specific power (W/kg)
LH2 tank	weight fraction

Fig. 2: Parameter list for key-technologies

Several missions, e.g. payload and range, were considered in order to scan the whole market of civil transport aircraft. In order to illustrate the results of such preliminary analysis, Fig. 3 shows the trends from the OAD approach for a regional aircraft with several possible energetic power chains. It focuses on a “regional” mission which consists of carrying 75 passengers on 1 000 km at a flight level (in cruise) of 5 000 m. Three technology-maturity levels are then considered, as referenced before. On this picture, the red marks correspond to two reference aircrafts, respectively ATR 72 and A320 (this last one assessed on this mission, e.g. with fuel suited for 1 000 km + reserves) [4].

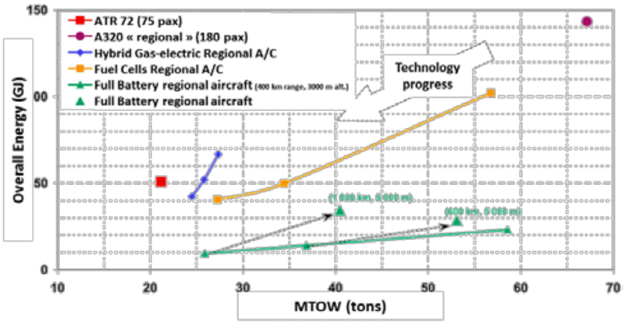

Fig. 3: L0 OAD results for a regional mission

Thus, if we consider for example a regional Aircraft using fuel cells as energy sources and distributed electric propulsion, the state-of-the-art situation gives an aircraft weighting close to 57 tons and using about 100 GJ energy for doing its mission. Using 2030 assumptions, for the same mission it requires only 50 GJ, close to an ATR 72, and weighs 34 tons. Pushing assumptions at the most promising horizon, this Electric Regional Aircraft appears to be close to present ATR 72.

Assessments done in that way have convinced both ONERA and CEATech experts that All-Electric-Aircraft (AEA) will be feasible and potentially affordable in the future. Hence, the key-technologies will have to be investigated in order to increase TRL and then to propose them to aircraft manufacturers.

2 Concept-planes overview

In 2014, a first pre-design exercise [5] has been done in order to illustrate the potential of such innovations in a first application-case based on the recent results of the UE funded PPlane project [6] dedicated to Personal Plane. Indeed, the need for a 4 to 6 seats small business aircraft, operated from downtown or close to urban area, able to cover ranges from 400 to 500 km in about two hours at low cruise altitude, up to 3 000 m AMSL (Above Mean Sea Level), has emerged from this project, with some requirements in terms of automation in order to be used by everybody without specific skills and qualification.

On the basis of this Top Level Aircraft Requirements (TLAR), an ONERA's engineer team has designed, at a conceptual level, two concept-planes of AEA which illustrate the compromise resulting from the use of several of the breakthrough technologies mentioned previously (Fig. 4 & Fig. 5).

Fig. 4 Three-surface concept-plane with distributed EDF at the wing trailing edge

Fig. 5: High-wing concept-plane with distributed EDF along the wing leading edge

2.1 Main Characteristics

Starting from main operational characteristics (TLAR) compliant with the CS23 regulations, an iterative multidisciplinary design process has been used to determine the main aircraft design characteristics (see Fig. 6):

- The propulsion is performed through 40 EDF located along the wing span in order to increase aerodynamic lift in low speed conditions, giving some STOL (Short Take-off and Landing aircraft) capabilities. Indeed, distributed propulsion promises dramatic increases in aerodynamic and propulsive efficiency, and potentially noise reduction.

- The propulsive force is also used to mainly control yaw and roll effects allowing stabilizers size reduction and finally, aircraft weight saving. However, it requires combining EDFs properly to ensure control laws (lateral stability). Flight performance analysis shows that the propulsive force must be controlled symmetrically at the same time and also in case of EDF failure on both sides of the wing.

- To be compliant with the CS23 certification rules and more particularly during the climb step in case of engine failure, flight performance analysis has shown that only 32 operational EDF are required.

- No complex Environmental Control System is required due to flight level (altitude < 3000 m).

- In our flight configuration, the on-board energy has been defined as follow:
    - Starting from the greatest propulsive force required during the take-off and considering electric motor (97 %) and engine power unit (95 %) efficiencies, an electric power of 400 kW is required;
    - For a range of 400 km, the consumed energy has been estimated with the following assumptions: 17 min for climb step (70 km), 78 min (330 km) for cruise and the descent steps and, roughly, 15 min for the safety reserve. To perform this flight, 400 kWh are necessary for the propulsion which leads, considering the other consumers, to a total energy of 500 kWh.
- The different scenarios evaluated through the multi-disciplinary approach show that the Polymer Exchange Membrane hydrogen Fuel Cell (PEMFC) concept is the more promising solution for the considered TLAR for providing the electric power (both for propulsion and systems), with the help of a battery pack for instantaneous power demands.

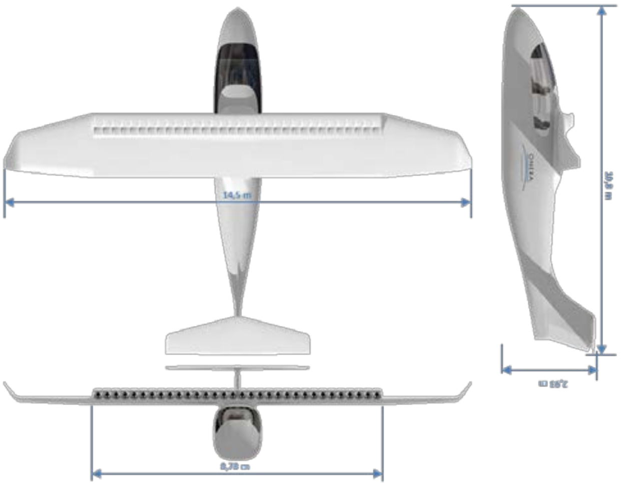

Fig. 6: 3 view drawing of the main configuration

Now, considering the high-wing concept-plane with distributed EDF along the wing leading edge, a MTOW (Maximum Take-Off Weigh) of 2 400 kg is assessed. The mass breakdown is as follows:

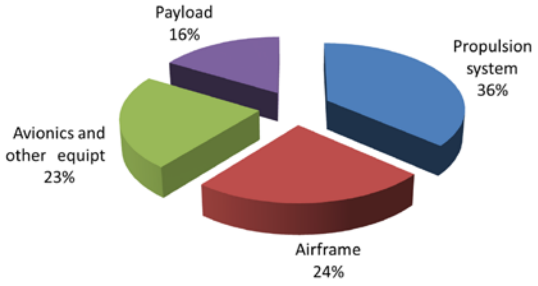

Fig. 7: Estimated MTOW for the high-wing concept-plane

2.2 Propulsion and Power System Architecture

An aircraft results from compromise between several viewpoints in order to fulfil some requirements, e.g. mission objectives and safety constraints. Conventionally speaking, this compromise concerns aerodynamics, structure, propulsion, performances and handling qualities, acoustic considerations and so on. For an AEA, beyond those considerations, several new coupling aspects appear with also new degrees of freedom in the design space. The required compromise comes from an iterative and multidisciplinary approach which considers all of these aspects. The following explanations regarding the main characteristics of the designed Propulsion and Power System (PPS) architecture are the result of this iterative multidisciplinary approach.

2.2.1 Distributed Propulsive Architecture

The first step is to define the optimal distributed propulsion architecture which would be compliant with the CS23 certification rules but also optimized to participate in the motion control of the airplane during flight.

As explained previously, the propulsive force must be controlled symmetrically at the same time on both sides of the wing. Consequently, starting from these considerations, an advanced propulsive architecture has been identified consisting in 10 clusters of 2*2 EDF as shown on Fig. 8 (one color for each cluster). Each EDF is also controlled individually which allows reconfiguration of the overall electric propulsion system.

Hence, a failure of one EDF – basic OEI (One Engine Inoperative) case – leads to the lack of a very small fraction of the thrust (1/40). Furthermore, the failure of one cluster of EDF leads to a lack of a limited fraction of 10 % of the overall thrust, and in that failure-case, the bi-symmetrical allocation of EDF along the span avoids any dissymmetrical thrust, which is critical for safety issues.

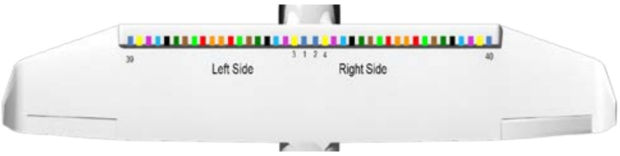

Fig. 8: Example of advanced propulsive architecture by EDF clusters allocation

2.2.2 Power Architecture

The next step is to design a safe and optimized advanced power architecture (Fig. 9) relevant with the EDF clustering.

Aiming to reduce the common failure points, each EDF cluster is powered by its own fuel cell system (PEMFC and high pressure hydrogen tank), battery stack with its Energy Management System (EMS) and its own electrical wiring interconnection systems (EWIS). To reduce the power architecture weight, a High Voltage Direct Current (HVDC at 135Vdc) distribution is chosen between fuel cell (available output level)/battery stack and EDF. This choice reduces the number of power conversion steps (DC/AC and AC/DC) and the number of wires in the power cables (two phases instead of three phases).

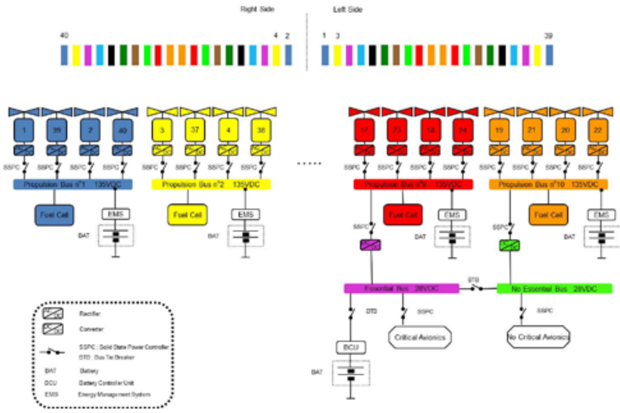

Fig. 9: Example of advanced power architecture.

As a result, an electrical system based on 10 primary power distributions has been selected, in which each primary distribution is composed of Busbar, Solid State Power Controller (SSPC) modules allowing electrical load control remote and cable protection, cable harnesses and inverter (DC/AC) at EDF level.

To supply the power to the other systems, two secondary distributions (called *essential* and *non-essential*) are designed with a 28 Vdc voltage. Each of them is connected to one primary distribution via a SSPC module and a DC-DC converter (135 Vdc to 28 Vdc). The *essential* secondary distribution is also connected to a dedicated li-ion battery system (autonomy 20 min) allowing to supply the power to the main bus if the two primary distributions are out of order. The two secondary distributions are linked by a Bus Tie Breaker (BTB) to transfer the electrical power between the *non-essential* and the *essential* buses.

To evaluate the electric power required by all others consumers, the embedded power of the Cirrus SR22 (2.4 kW) has been used as a reference to which additional power, roughly 1.6 kW, has been added for the new on-board systems (high demanding and redundant Flight Control System). Taking into account the redundancy of the power system, an additional capacity of 8 kW has been taken into account for the hydrogen fuel cells.

2.2.3 Components evaluation

The next step is now to evaluate the main characteristics of each component of our proposed advanced power architecture.

First, each fuel cell unit system is designed to provide a power of 40 kW (to supply 4 EDF, 10 kW each), except two fuel cell systems (44 kW) to supply in addition on-board equipment.

To reduce the PEMFC weight (and volume) and preserve the power capacity at different flight levels (from ground up to 3 000 m), the inlet pressure has been set to 1.8 bars. The increasing of fuel cell pressure allows raising its rated

power. This 1.8-bar pressure rate results from the use of two air compressors.
In these conditions and with a fuel cell efficiency of 0.6 a power density of 1.8 kW/kg is assumed. Thus, the gross weight of the PEMFC system (i.e. 10 fuel cells with their hydrogen tanks, associated with air compressors) is about 226 kg and its volume reaches 1 m^3.
For an embedded energy of 500 kWh, it needs to store 30 kg of hydrogen (at 700 bars) in 10 carbon fiber composite (CFC) material tanks of about 25.5 kg and 0.051 m^3 each (with a diameter and length of 0.3 m and 1.63 m respectively).

The instantaneous power demands will be assumed by battery packs which are linked in parallel to each fuel cell systems and controlled by its EMS.
In our case, the "dynamic" part has been estimated at 10 % of total propulsive energy of our flight configuration either 40 kWh. Considering an energy density of 300 Wh/kg, we obtain a battery packs weight of about 133 kg.

Second, each EDF supply chain is protected by a SSPC module of 10 kW under a HVDC voltage of 135Vdc. Based on the assumption that commercial SSPC modules will be used, a power density of 15 kW/kg has been estimated from data sheets, leading to a SSPC weight of about 27 kg.

From the aircraft geometry defined by CAD, the power harnesses length of the propulsive part is close to 114 m. The environmental flight conditions (altitude) and installation characteristics analysis, give a wire gauge of "8" with an average linear weight of 0.130 kg/m. The corresponding cables weight is about 39 kg including their installation penalties (estimated at 30 % of the cable weight).

The overall weight of (DC/AC) inverters located in front of EDF is about 100 kg with a power density close to 4 kW/kg. Finally, the assumption that a power density of 5 kW/kg was available at EDF level has been done and thus the EDF system weight about 80 kg.
The total weight of advanced power architecture about 890 kg has been summarized in Fig. 10.

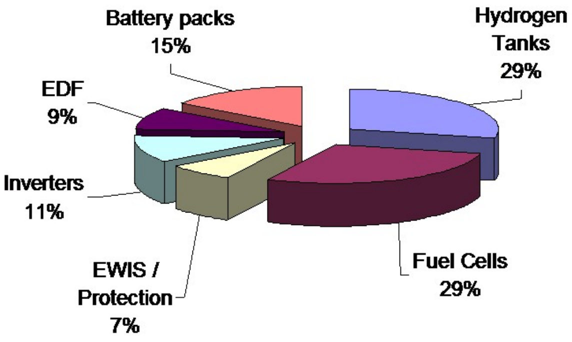

Fig. 10 Summary of weight of advanced power architecture

3 DEP investigations

In order to start investing some of these technologies, ONERA recently decided to focus effort on the distributed propulsion and its effects on aerodynamics and control, and controllability of such planes using unconventional, distributed and heterogeneous actuators.

Thanks to CARNOT Funding, a project, called AMPERE, has been launched to analyze the behavior of the DEP by combining computational and experimental approaches. For that, a wind-tunnel powered mock-up of one of ONERA's concept-planes has been designed and manufactured. This powered mock-up will be tested soon in ONERA's L2 facility (located at Lille Center) in order to capture DEP behavior for aerodynamic assessment and flight control law definition.

3.1 Powered mock-up

3.1.1 Mock-up main characteristics

The L2 facility which will be used in our demonstration is a low speed wind tunnel (19 m/s). Due to its geometrical characteristics, no wall effects occur on a mock-up about 3 m span. Considering L2 facility limitations and the will to power our mock-up using COTS components, especially EDF, a scale of 1:5 has been finally chosen. This scale leads to a 2.9 m span mock-up with a length of 2.16 m and a constant chord of 0.4 m on the inner wing, on where EDF are located. Thanks to L2 WT characteristics the local Re is 534000. Other main characteristics of our scale model are listed hereafter.

Characteristic	Unit	Scale 1	Scale 1/5
Airfoil surface	m²	25.86	1.034
Horizontal tail surface	m²	3.80	0.152
Horizontal tail wingspan	m	4.26	0.852
Internal volume	m^3	6.35	0.051 (51 l)
Fuselage length	m	10.80	2.160

As stated before, the use of COTS components and a lack of available solutions led us to consider 50 mm diameter Electric Ducted Fan (EDF) rather than 40 mm diameter ones, which was suggested by homothetic rule. In line with other considerations regarding geometry, symmetrical arrangement and overall thrust level, only 32 EDF will be used on this mock-up.

On this basis, and considering the main objectives for these wind tunnel experiments, the design of the mock-up has been improved through some focused investigations regarding mainly, wing airfoil, EDF performances, EDF integration in term of chord location, setting and depth of burying, control surfaces sizing and finally the local geometry of air intake and exhaust including tail cones of EDF.
In addition, more related to the experimental requirements, a special attention has been paid on electrical architecture, EMC compatibility and thermal environment of components integrated in it.

Some of those considerations will be partly detailed hereafter.

3.1.2 Aerodynamic analysis of the EDF integration

As described before, an aerodynamic analysis has been done in order to fix the location of EDF in order to mainly maximize high lift effects.

Starting from some past investigations [5][7], RANS 2D and 3D numerical computations have been done using in-house ONERA CFD tool elsA.
The aim of these simulations was to compare multiple configurations (wing airfoil, location and setting, fan diameter, etc.) considering several criteria such as [CL, CD], stall behavior and pitching moment wrt thrust level.
For example, the Fig. 11 depicts the pressure field obtained by elsA 2D RANS computation on leading edge EDF location, for a certain level of thrust.

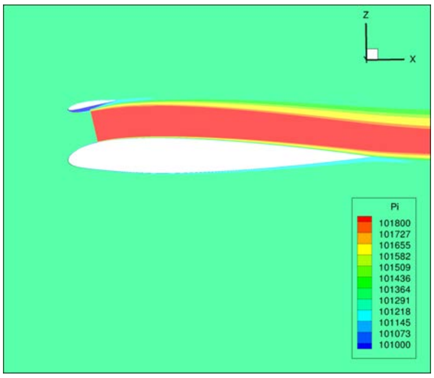

Fig. 11 - Example of 2D RANS CFD calculation simulating a turbine location to the leading edge.

The second objective of aerodynamic computations was related to the detailed design of intake and exhaust parts of EDF installation. To do that, 3D CFD RANS computations have been performed through elsA software, with the use of actuator disk to simulate the real EDF used. An example of result is shown on Fig. 12.

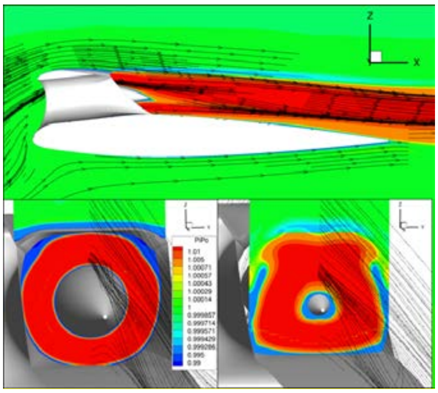

Fig. 12 Example of 3D CFD calculation

3.2 Definition of the electrical propulsion

In parallel with the determination of the scale model, components of the electrical propulsion chain (EDF, Electronic Speed Controller or ESC, power supply, wiring, electronic modules for the management of the 32 ESC and the capture of motor RPM) have been either chosen, defined and/or characterized and finally purchased or set-up and built.

WeMotec MicroFan EDF has been chosen after a first set of experiments on a dedicated test bench, with 6 COTS EDF candidates.
Then, a second set of experiments (see Fig. 13) was done later on the 32 EDF (completed by the same number of ad-hoc ESC), in order to model their behavior in term of laws such as [thrust, Intensity] = f(RPM), considering voltage and then to be able to drive it through ad-hoc electronic modules.

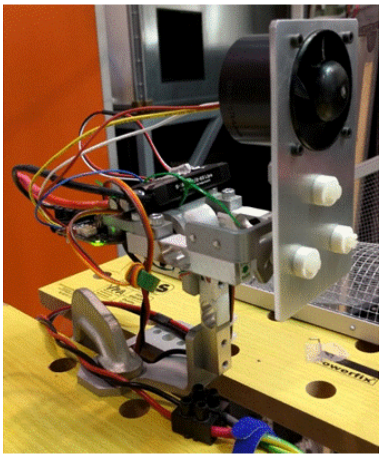

Fig. 13 - EDF test bench, adapted from RCBenchmark *Dynamometer Series 1580* thrust stand

From those experiments and considering mock-up installation in the L2 facility, the sizing of the electrical power supply concluded on the use of 32 independent sources supplying each 600 W (as each EDF requires an electrical power around 450 W to reach their maximum speed, close to 60000 rpm).

EDF and ESC experiments confirmed also that thermal management of ESC, which will be confined in the wing body of the mock-up, is of first importance. Motor controllers can dissipate a lot of heat (roughly 70 degree Celsius) versus their solicitation (efficiency).

Moreover, the 32 twisted cables which supply each one EDF will be also integrated close to the ESC in the central part of the wing (between two spars) where volume is limited. This implies to take into account the harness losses and also the thermal contribution in that space.
As a consequence, a cooling system has been designed and integrated in the mock-up. It uses compressed air, coming from external L2 facility, which will be diffused locally to each controller by small vinyl tubes (see Fig. 14) and extracted close to ailerons at the inner wing.

Fig. 14 – View of cooling system

Considering these constraints, the maximum cable length between a voltage source and a controller has been estimated to 8 m and the output of the voltage source will be of 18 volts to have a good performance of EDF.
In order to test the overall electric architecture of the mock-up propulsion system, including electronics for ESC driving and motor monitoring, all components are integrated on a ground test bench (see Fig. 15).

Fig. 15 – Ground test bench for propulsion architecture validation

This functional and material validation, including verification of electronic compatibility will be done during the summer 2016 before integration of these components in the mock-up.

3.3 Mock-up detailed design and manufacturing

All of previous focused studies led to set the external geometry of the mock-up through a CAD model and to freeze the requirements for the detailed design and manufacturing of the mock-up.

Detailed design (assuming internal arrangement of structures) and manufacturing have been subcontracted to a French SME, Aviation Design, who is actually involved in several activities regarding scaled flying demonstrators for proof of concepts or technologies.
The detailed CAD model of this mock-up has then been created (see Fig. 16) in close relationship with ONERA engineers, fulfilling the set of ONERA requirements coming from tasks detailed before.

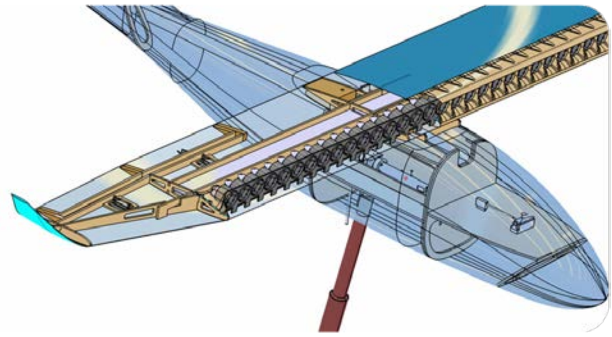

Fig. 16 – View of the CAD model

The mock-up is mainly in carbon fiber composite materials with some metallic parts either for WT balance binding or electric components thermal dissipation. The manufacturing process uses several molds in Labs materials to be compliant with geometrical tolerances required.

Fig. 17 – Picture of the mock-up

4 Conclusions

Electric propulsion for aircraft is a promising solution for reducing environmental impact of aviation together with a decrease of fossil energy dependency, considering also that passenger will accept in the future to fly differently: lower, slower and probably with more bounds for a given range than today.

Based on recent ONERA’s investigation, this propulsive innovation requires to address several key-technologies and ONERA’s experts are convinced that Distributed Electric Propulsion, using distributed hybrid energy sources based on coupling fuel cells and batteries, will be the basis for the emergence of All Electric Aircraft, first for small business operations but potentially for more demanding ones.

Therefore, the AMPERE project aims to increase know-how regarding these new technologies and will help aircraft manufacturers / aircraft designers to better understand pros & cons, and also better integrate them in future configurations of aircraft able to fulfil societal needs and reduce environmental impact of aviation.

In that way, ONERA intends to participate in the future of Aviation and is ready to go with research and industrial partners to promote, develop and make effective All Electric Aircraft especially using distributed propulsion.

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